Automated characterization of CCD detectors for DECam

CCD Packaging and Testing Team
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FOR THE DARK ENERGY SURVEY COLLABORATION

ABSTRACT

The Dark Energy Survey Camera (DECam) will be comprised of a mosaic of 74 charge-coupled devices (CCDs). The Dark Energy Survey (DES) science goals set stringent technical requirements for the CCDs. The CCDs are provided by LBNL with valuable cold probe data at 233 K, providing an indication of which CCDs are more likely to pass. After comprehensive testing at 173 K, about half of these qualify as science grade. Testing this large number of CCDs to determine which best meet the DES requirements is a very time-consuming task. We have developed a multistage testing program to automatically collect and analyze CCD test data. The test results are reviewed to select those CCDs that best meet the technical specifications for charge transfer efficiency, linearity, full well capacity, quantum efficiency, noise, dark current, cross talk, diffusion, and cosmetics.

1. INTRODUCTION

The Dark Energy Survey (DES) will measure dark energy parameters using four complementary techniques: weak gravitational lensing, galaxy cluster counting, baryon acoustic oscillations, and supernovae. The data will be collected during a 5000 square degree survey of the southern galactic cap and a smaller repeated supernovae survey during 525 nights of observing from 2011 to 2016. The survey requires a new instrument, the Dark Energy Camera (DECam), to be built and installed at the prime focus of the 4-meter Blanco telescope at Cerro Tololo in Chile. For the status of DECam, see *Status of the Dark Energy Survey Camera (DECam) Project,* submitted by Brenna Flaugher (Paper 7735-12) [1].

DECam has a 3 square-degree field of view accomplished using a new optical corrector with one of the largest lenses ever produced for optical astrophysics and an 8-filter housing that will contain g,r,i,z, and Y filters. The imager is a 520 Megapixel digital camera comprised of sixty-two 2048 x 4096 CCDs. An additiona1 twelve 2048 x 2048 CCDs will be used for guide and focus applications. The CCD readout is performed using a system based on the National Optical Astronomy Observatory (NOAO) Monsoon electronics.

The CCDs are 250-micron thick, back-illuminated, red-sensitive devices designed by Lawrence Berkeley National Laboratory (LBNL) [2]. The CCDs are fabricated with processing steps at both DASLA Semiconductor and LBNL's Microsystems Lab. The CCD is back-illuminated through an anti-reflection coating and is fully-depleted by application of bias voltage, typically 40 volts, to a thin backside conductive layer. Photons create holes in the thick substrate, which is n-type silicon, that are collected in a p-type channel. High quantum efficiency in the near-infrared

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wavelengths results because the CCDs are thicker than traditional thin astronomical CCDs. The LBNL devices are 3-phase CCDs. The pixel geometry is 15-micron square with a 0.27" plate scale.

Production packaging began in early 2009. As of May 2010, we have packaged 209 2k x 4k imaging CCDs with 88 of those meeting the science requirements (Fig. 1-1). We have also packaged 23 2k x 2k guide and focus CCDs with 13 meeting the requirements (Fig. 1-2). This rapid and steady testing rate was accomplished thanks to the development of automated temperature and vacuum controls, automated test sequencing, and automated data analysis developed at Fermilab. These systems are described below.

For a detailed discussion of the characterization of the DECam CCDs, see *Focal plane detectors for the dark energy survey,* submitted by Juan Estrada (Paper 7735-61) [3].

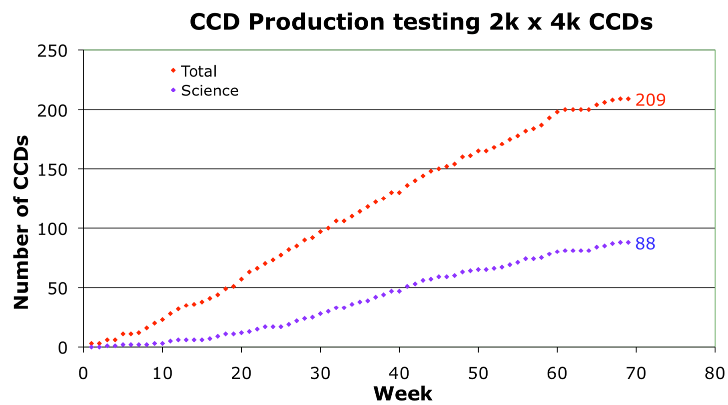


Fig. 1-1 CCD production and testing progress for 2k x 4k CCDs

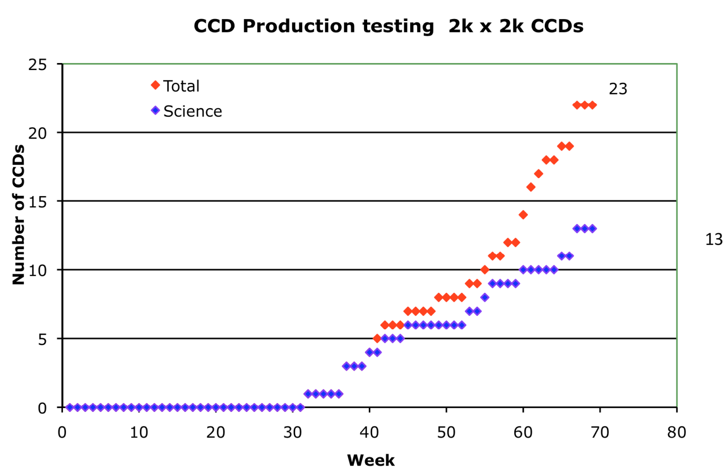


Fig. 1-2 CCD production and testing progress for 2k x 2k CCDs

2. PRODUCTION AND PACKAGING

The CCDs are produced by DALSA and LBNL in 24-wafer "Lots" with four 2048 x 4096 pixel CCDs, one 2048 x 2048 pixel CCD, and four 1024 x 512 pixel CCDs on each wafer (Fig. 2-1). The processing starts at DALSA. Three wafers per lot are finished at DALSA and are 650 microns thick, too thick to be fully depleted at the desired substrate voltage. The remaining 21 wafers are sent to LBNL for thinning to 250 microns and for the backside-processing steps that complete the CCD production. LBNL ships the CCDs to Fermilab, along with results from readout tests of each 2k x 4k CCD. This test data is accumulated using a cold probe station operating at temperature 233 K. Defects are identified and classified automatically using data taken at different clock and substrate bias voltage levels. Although 233 K is warmer then the expected operating temperature of 173 K, this data is vital for determining those devices that are potentially of high quality and, therefore, suitable for packaging and testing.

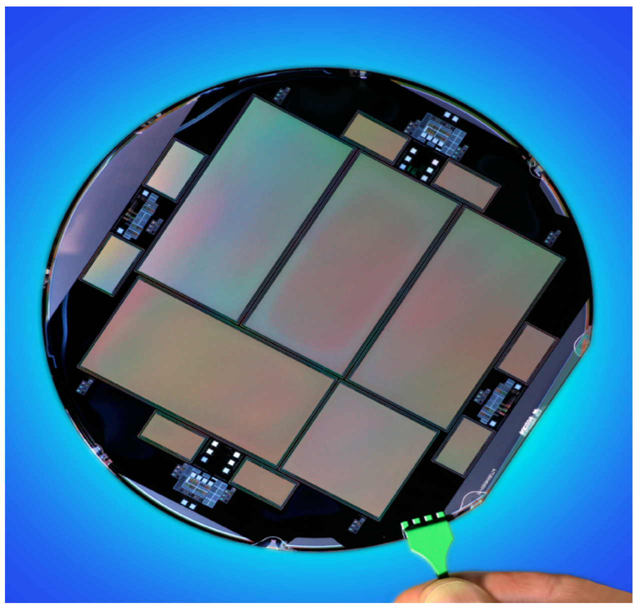


Fig. 2-1 Each wafer has four 2048 x 4096 pixel CCDs, one 2048 x 2048 pixel CCD, and four 1024 x 512 pixel CCDs

The CCDs are mounted on packages at Fermilab. The 4-side-buttable package is called a "Pedestal Package" (Fig. 2-2). The CCD is held flat while it is glued to an assembly comprised of an aluminum nitride circuit board, aluminum nitride spacer, and flat Au-plated INVAR foot. The CCD is wirebonded to the aluminum nitride circuit. The aluminum nitride circuit has an Airborn 37-pin N-series two-row female connector for connection to the CCD readout electronics (Figure 2-3). The details of the CCD package are presented in [4].

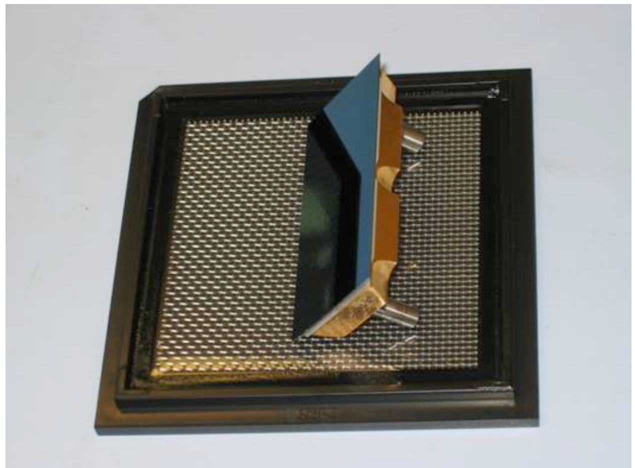


Figure 2-2 A 4-side-buttable pedestal package showing the front side of the CCD, which is dark because of the anti-reflective coating. The cutouts in the Au-plated INVAR foot allow the wirebonding machine viewing access to the AlN circuit and CCD bond pads.

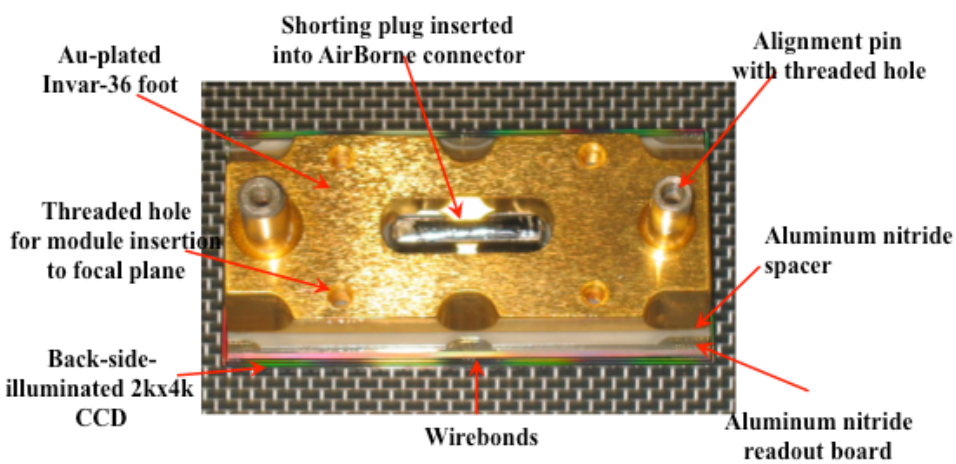


Figure 2-3 View of underside of a pedestal package sitting on a gel-pack showing the Au-plated INVAR foot, two alignment pins, the connector, the edge of the AlN blank with cut-outs for the wirebonds and the edge of the CCD

3. TECHNICAL SPECIFICATIONS

Technical specifications for the CCDs were determined from the Dark Energy Survey science requirements. These are listed in Table 3-1. In particular, these CCDs have high quantum efficiency in the wavelength range 800-1050 nanometers. Because they are 250 microns thick, fringing is expected to be minimal in the f/3 beam of the Blanco 4-meter primary mirror. The CCDs are required to be read out in 17 seconds, the telescope slewing time during the survey. That readout rate corresponds to 250 kpixels/second at <15 e^- noise. Typical observing is expected to produce a point-spread-function (PSF) of 0.9". The technical requirement is that the instrument delivers a PSF < 0.55" resulting in a budget for charge diffusion of 7.5 microns, corresponding to 0.14". The CCDs are required to be flat, uniformly thick, and form a focal plane with a peak-to-peak variation of less than 30 microns. (Detector flatness on < 1 cm^2 scales should be ≤ 3μm. Detector flatness between adjacent ≤ 1cm^2 areas on a given CCD should be ≤ 10μm.) The CCDs are required to be of high quality; the mean percentage of pixels that are out-of-tolerance will be < 0.5% with no single device having more than 2.5% out-of-tolerance pixels.

Pixel array	2048 · 4096 pixels
Pixel size	15 μm x 15 μm
# Outputs	2
QE(g,r,i,z)	60%, 75%, 60%, 65%
QE Instability	<0.3% in 12-18 hrs
QE Uniformity in focal plane	<5% in 12-18 hrs
Full well capacity	>130,000 e^-
Dark current	<~25 e^-/hr/pixel (at 173 K)
Persistence	Erase mechanism
Read noise	< 15 e^- @ 250kpix/s
Charge Transfer Inefficiency	$<10^{-5}$
Charge diffusion	1D σ < 7.5 μm
Cosmetic Requirements	<# Bad pixels> <0.5% None worse than 2.5%
Linearity	1%
Package Flatness	10 microns.

Table 3-1 DECam CCD technical requirements and the typical characteristics of the LBNL fully-depleted CCD.

4. CCD TESTING INFRASTRUCTURE

CCD packaging and testing is carried out in the Silicon Detector Facility (SiDet) at Fermilab. This facility is well-known for design, assembly, and testing of silicon strip and pixel vertex detectors for use in elementary particle physics experiments at Fermilab and at CERN. SiDet has numerous cleanrooms, wirebonding machines, optical and mechanical measurement systems, and probe systems, as well as the infrastructure required to work with and protect the electrostatic sensitive CCDs from inadvertent damage. Finally, SiDet has the skilled engineers and technicians required to perform this kind of work.

5. CCD OPTICAL BENCH

The CCDs are tested using the optical setup shown in Fig. 5-1. A single CCD is housed in a thermally-controlled vacuum dewar that is cooled to the operating temperature of 173 K using LN2. A standard set of optical equipment is used to illuminate the CCD at the desired wavelength. A shutter controls exposure times. The optical path is intended to be light-tight, but it is not perfect, as will be mentioned below. All CCD test sequencing use automated TCL imaging scripts. The filter wheel and monochrometer are controlled using GPIB through the TCL interface. The vacuum dewar also contains an ^{55}Fe radioactive source housed on an arm that can be rotated to a location in front of the CCD. This test stand has been replicated three times so that we can test four CCDs in parallel. We usually test three in parallel, which is sufficient to keep up with the packaging rate. There are two additional testing stations, one used for flatness studies and the other for special studies that are not part of the routine testing.

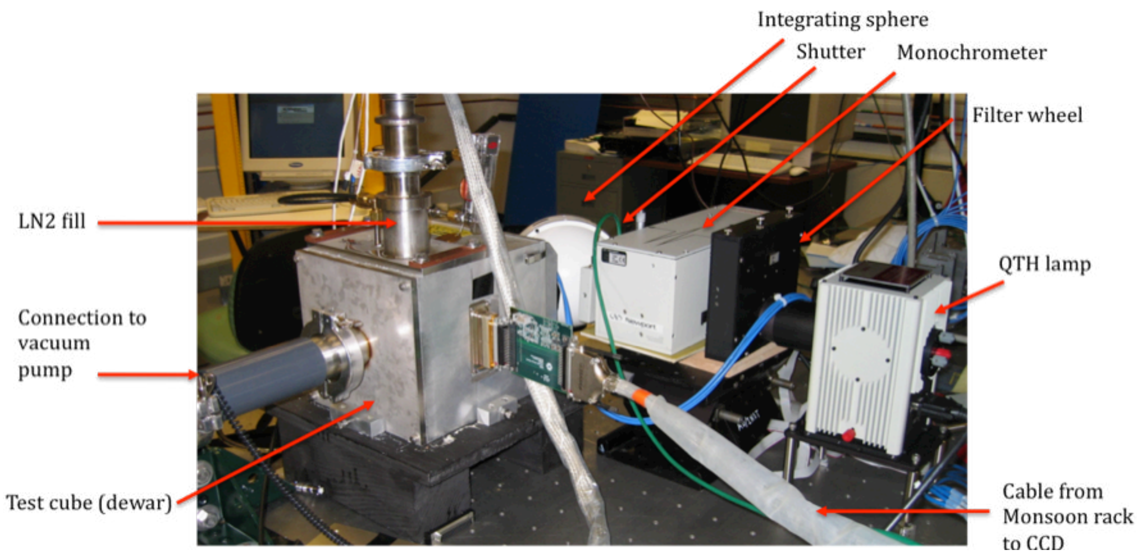


Figure 5-1 Typical CCD optical test stand. From right to left, the light source (QTH lamp), filter wheel, monochrometer, shutter, integrating sphere with photodiode installed on one port read out by an Oriel power meter. The sphere is connected to the dewar by a light-tight baffle (not visible in the photo). The light enters the vacuum dewar through a fused-silica window (facing away). The CCD package is mounted on a cold-plate that faces the window. It is cooled with liquid nitrogen.

6. AUTOMATED TEMPERATURE AND VACUUM CONTROL

Each testing station has its own turbo vacuum pump and Lakeshore temperature controller (Fig. 6-1). The LN2 fill is interlocked to prevent filling until the vacuum is below 2×10^{-4} Torr. There is a LabVIEW-based automated LN2 fill system for each testing station. The automated heater controller keeps the CCDs at 173 K via a PID control loop. Stable temperature with fluctuations ~0.1 K is achieved with the PID loop.

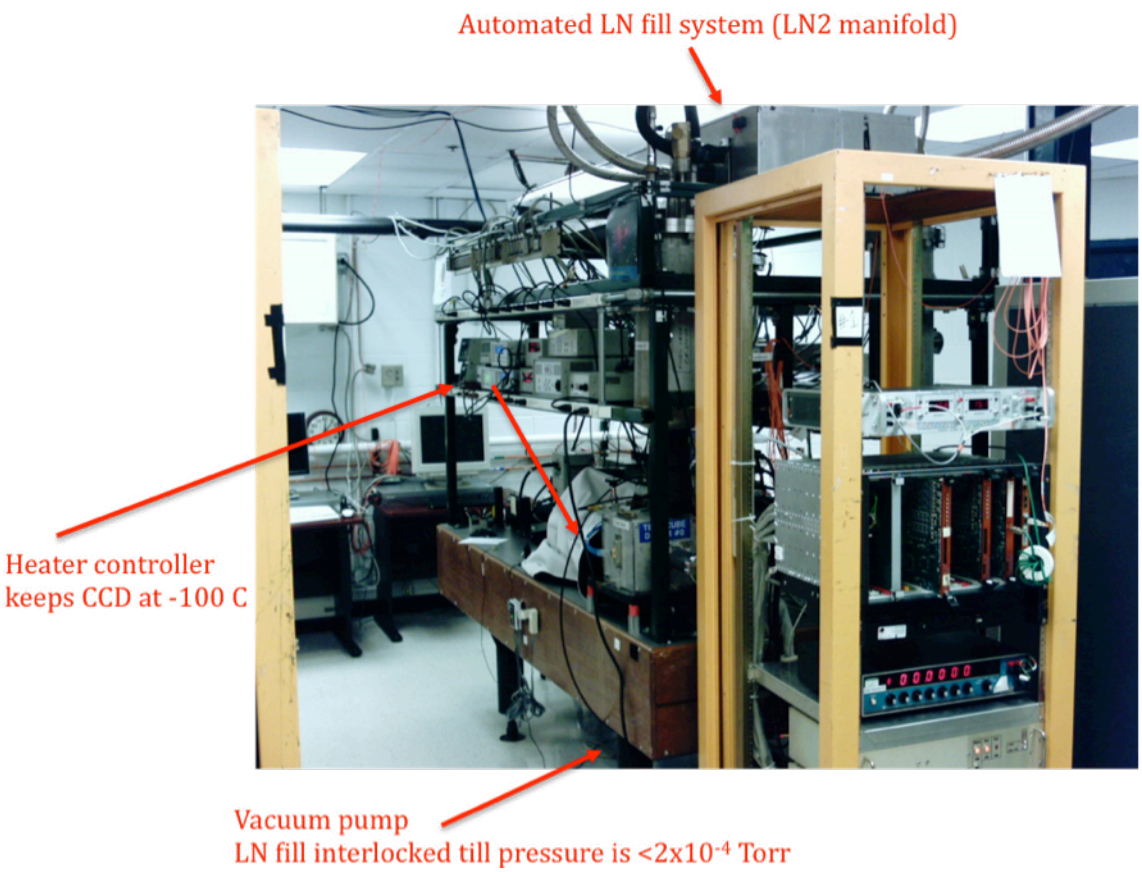


Fig. 6-1 Vacuum and temperature control system

Fig. 6-2 shows a CCD inside mounted in the DES pedestal package. The exterior walls of the dewar are made of aluminum. Inside, there is a copper box that isolates the cold parts from the exterior walls. Fig. 6-3 is a view from the front of the dewar with the cold plate and cold finger used to mount the CCD removed to provide a view of the LN2 reservoir and control valve. The small diameter tube is used to vent evaporated nitrogen. A valve is used to control the flow of gas. This sets the level of LN2 inside the dewar.

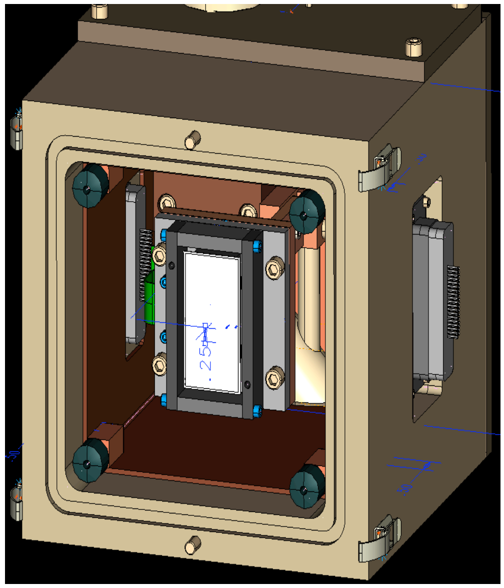


Fig. 6-2 View of pedestal package mounted on the cold plate inside the test dewar

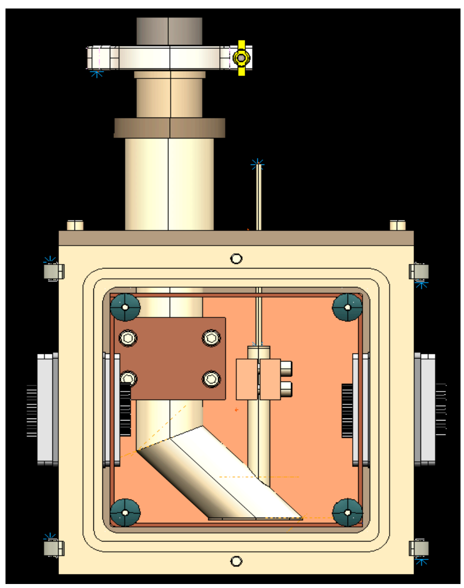


Fig. 6-3 View with the CCD and cold plate removed to provide a view of the LN2 reservoir and vent

7. AUTOMATED TEST SEQUENCING

7.1 Software

A modified NOAO Monsoon system is used for testing. Descriptions of the modified Monsoon system can be found in: *System architecture of the dark energy survey camera readout electronics* submitted by Terri Shaw (Paper 7735-123) [5] and *Readout Electronics for DECam* submitted by Javier Castilla (Paper 7735-311) [6] in these proceedings.

The images are stored using standard FITS format. TCL-based software provides automatic sequencing of test procedures. The software sets device parameters (clock voltages, bias levels, etc.), controls of the shutter, monochrometer, and filter wheel, and controls readout of the CCD by the NOAO Monsoon system, generating >500 36-MB FITS images. The user interface is shown in Fig. 7-1.

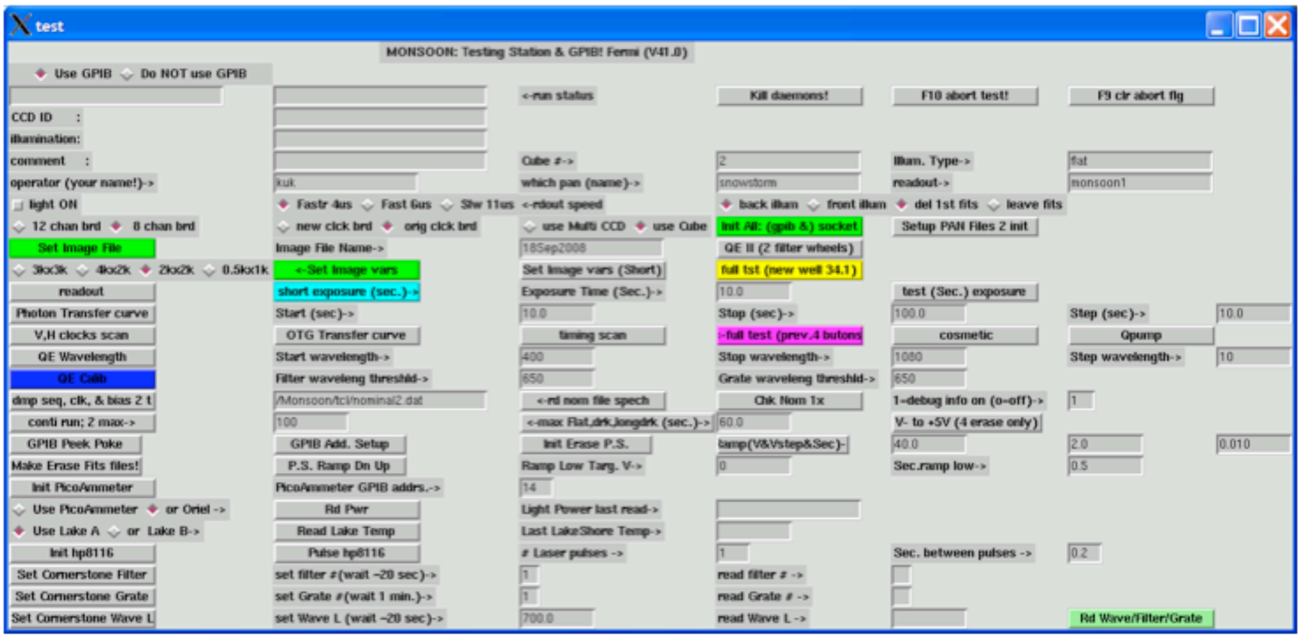


Fig. 7-1 Image of the GUI used to initiate test sequencing. There are options to run each test (as photon transfer, cosmetics, etc.) independently or to run an entire suite of tests, as all of Stage 1 or Stage 2 tests (described below).

7.2 Hardware

The rack of Monsoon boards and power supplies, the shelf of instruments (Lakeshore controller, lamp power supply, power meter), and cabling are shown in Fig. 7-2. Note that this is one of three complete testing stations located on the optical bench. The two other systems are on the far side of the optical bench, hidden from view in the photo.

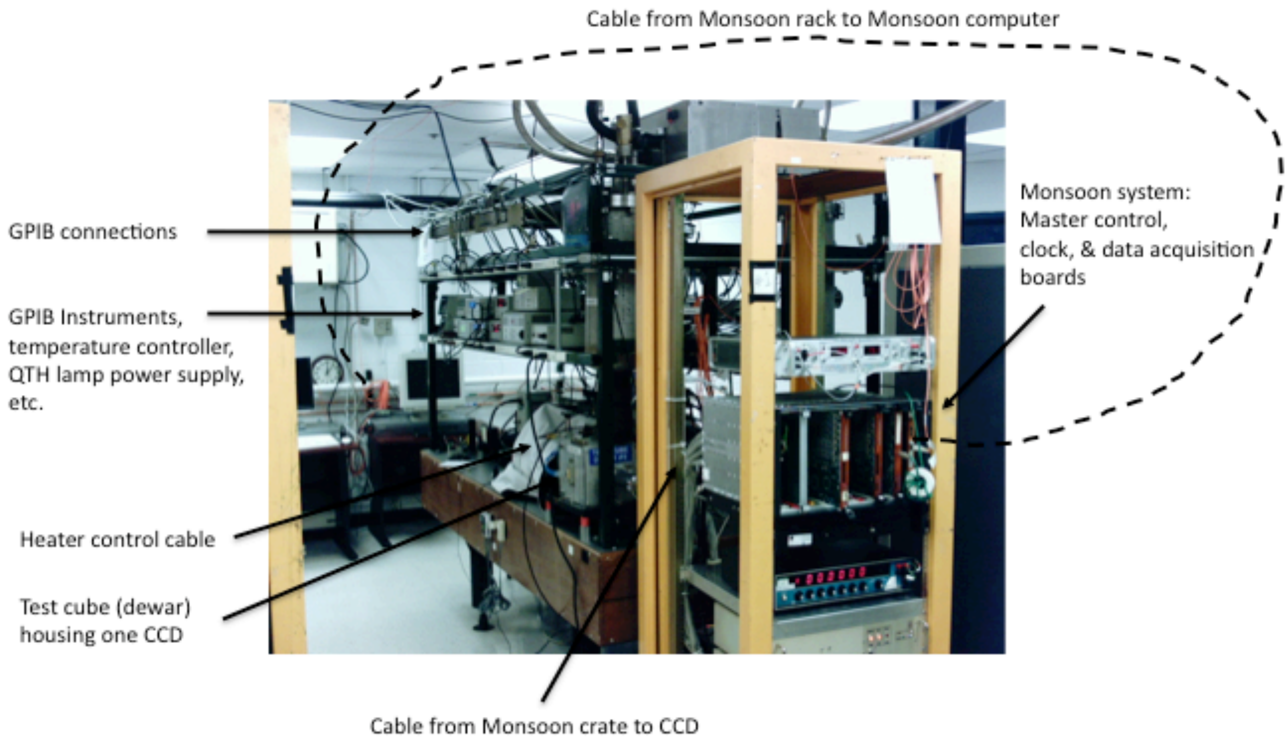


Fig 7-2 CCD test equipment and cabling

7.3 CCD testing sequence

Device testing is done in two "stages", with the better devices undergoing all tests and lower quality devices rejected as quickly as possible.

Stage 1 testing is performed on every packaged device. These tests are completed during the first day of testing. Stage 1 tests include: a photon transfer curve (providing gain, full well, and linearity); measurement of CTI, using extended pixel edge response (EPER) measurements, noise, and defect dependence over a range of clock voltages; output gate transfer, a test which studies charge injection and threshold voltage; charge-pumping to detect traps; and a series of dark and flat exposures to test for cosmetic defects. Devices passing Stage 1 testing will remain cold for further studies.

Stage 2 testing requires a second day to complete. These tests are carried out in the same vacuum dewar as the Stage 1 tests, therefore they don't require warming up the CCD nor transfer to another test stand. Stage 2 tests include dark current, charge diffusion, and QE vs. temperature and noise vs. temperature measurements. We expect most devices that passed the Stage 1 tests will also pass the Stage 2 tests.

The shape of every CCD is measured, including flatness and thickness, and the "visible knife-edge test" is used to look for uneven regions. A subset of the CCDs has been tested using the confocal chromatic displacement measurement system from Micro-Epsilon Corp. Details are presented in reference [7].

7.3.1 Stage 1 testing

After the initial setup, Stage 1 testing is performed automatically without further operator intervention. Stage 1 takes about 9 hours and results in 550 images (~20 GB of data).

The initial setup includes checking the clock voltages on a scope and checking the telemetry to verify that all operating parameters are nominal. The tests have been tailored for a fixed lamp level that yields 27,000 e- for a 10-second exposure. It is desirable to avoid changing the lamp power, because it takes time to stabilize. Once the operator sets the level, no further manual control is required. When a different illumination level is required for a test, the exposure time is automatically changed or a neutral density filter is automatically inserted in the optical path. The wavelength is selected via GPIB-controlled monochrometer and insertion of the corresponding order-sorting filter.

A complete listing of Stage 1 tests with a brief statement of the purpose and procedure of each test is shown in Table 7-1.

Stage 1 tests	Number of images
Photon transfer curve Purpose: Measure linearity, gain, and full well Procedure: Sweep exposure time (increasing and decreasing) from 10 s to 90 s in 10-second intervals	36
Photon transfer curve- Low light level Purpose: Measure linearity and gain at low light levels Procedure: Sweep exposure time (increasing and decreasing) from 5 s to 215 s in 20-second intervals	44
Clock voltage scan Purpose: Measure CTI and noise over a range of clock voltages (increasing and decreasing) Procedure: Sweep each voltage (V+, V-, H+, H-) independently, keeping the others at their nominal value, and measure CTI via the EPER method for each voltage setting	80
Output gate transfer Purpose: To study charge injection and threshold voltage Procedure: V_{OTG} is varied for different values of V_{REF}	77
Cosmetics Purpose: Measure the percentage of cosmetic defects Procedure: From a series of dark and flat images and their ratios, test for hot, dark, and nonlinear pixels	90
Quantum efficiency Purpose: Measure relative QE Procedure: Measure QE using exposures at wavelengths from 40 nm to 1100 nm in 10-nm increments	136
Traps Purpose: Detect traps deeper than 700 e- Procedure: Look for traps filled during charge pumping	120
Thumbnail image of all photon transfer and clock scan images Purpose: To check for development of features (as light bulbs, bright edge glow) that may occur at non-standard biases and exposure levels Procedure: Create FITS images of a tiling of all images	
Total	550 (20 GB)

Table 7-1 Description of Stage 1 tests

7.3.2 Stage 2 testing

Unlike Stage 1 testing, Stage 2 testing requires some manual intervention. We found that our optical path is not sufficiently light-tight to perform a measurement of dark current. Therefore, before taking images for dark current analysis, we manually disconnect the dewar from the optical path and install a blank-off plate to eliminate light leaks (Fig. 7-3).

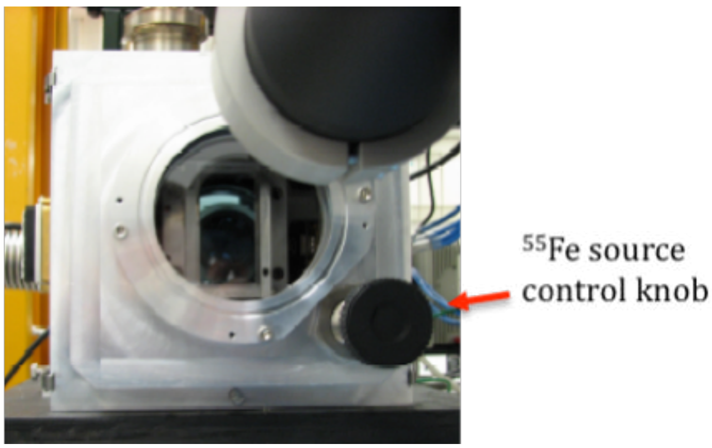


Fig. 7-3 Remove baffle and install a blank-off plate in front of window to eliminate light leaks for dark images. A 2k x 4k CCD can be seen inside the dewar through the fused silica window. The ^{55}Fe source can be rotated in front of the CCD via the control knob.

We measure diffusion from images exposed to ^{55}Fe at five different substrate voltages. Each dewar contains an ^{55}Fe radioactive source housed on an arm that can be rotated to a location in front of the CCD. The insertion of the ^{55}Fe source has not been automated, so an operator must manually rotate the source into the field of view of the CCD (Fig. 7-3). It takes an operator about 20 minutes to gather the ^{55}Fe images. We also use one of the ^{55}Fe exposures (the one taken with the substrate voltage at the nominal setting of 40V) to perform a measurement of CTI. This measurement of CTI complements the CTI measurements made via the EPER method in Stage 1.

The first steps of Stage 2 take several hours. For the final step, we turn off the LN2 flow and the heater. Images are then taken repeatedly while the CCD first gets a bit colder and then slowly warms up to room temperature, This takes about 8 hours and generates an additional ~10 GB of data.

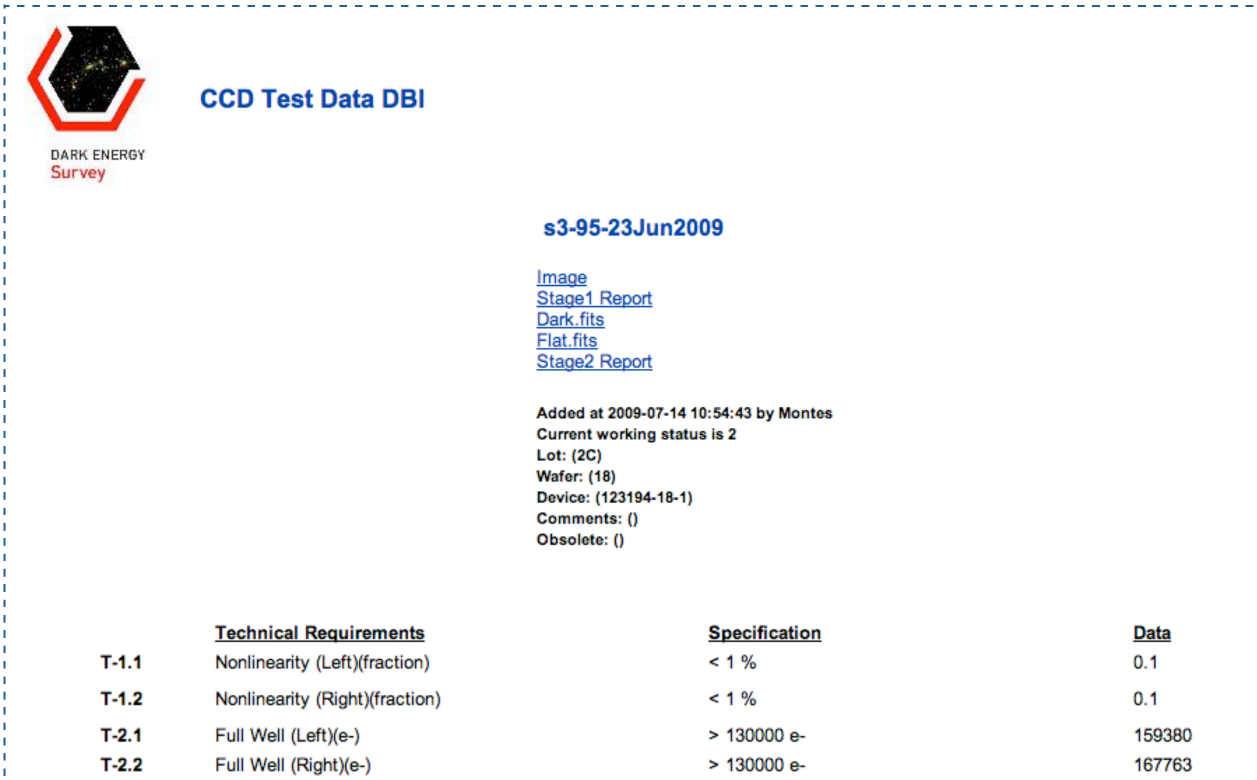
A complete listing of Stage 2 tests with a brief statement of the purpose and procedure of each test is shown in Table 7-2.

Stage 2 tests	Number of images
Dark current Purpose: Measure dark current Procedure: Measure signal level from the median of 10 overscan-subtracted and bias-subtracted 400-second dark images	20
Diffusion Purpose: Measure diffusion as a function of substrate voltage Procedure: Expose the CCD to ^{55}Fe at five substrate voltages (20V, 30V, 40V, 50V, 60V)	10
CTI with ^{55}Fe Purpose: Measure CTI Procedure: Use x-ray transfer method of measuring CTE. Use the V_{sub}=40V image from the set of images used for diffusion	
Thumbnail image of ^{55}Fe exposure Purpose: To check for development of features (as light bulbs, bright edge glow) that may occur at elevated V_{sub} Procedure: Create a FITS image of a tiling of all ^{55}Fe images using DS9	
Post ^{55}Fe photon transfer and dark current Purpose: To check that no changes are seen in the CCD gain, linearity , and dark current after elevating V_{sub} Procedure: Take data for a mini photon transfer curve with maximum exposure time of 50 s instead of 100 s as is done in Stage 1 and take three 400-second dark images to measure the dark current to ensure that the dark current has not changed	21
Warmup Purpose: Monitor the CCD as it slowly warms up to observe QE and dark current as a function of temperature Procedure: Flat and dark exposures (10 s flat, 10 s dark, 400 s dark) are taken repeatedly while the CCD is warming up after all other testing is complete. These images are used to generate plots of QE(1000 nm) vs. Temperature and Dark current vs. Temperature. The warmup is done by turning the LN and heater off. The CCD first gets a bit colder and then warms up slowly. It takes ~8 hours to warm up the CCD with the heater off.	200-400
Total	250-450 (>10 GB)

Table 7-2 Description of Stage 2 tests

8. AUTOMATED ANALYSIS

A script runs automated analyses of the test data for each CCD. First it checks that all the required images exist. Then it executes the analysis codes. Next, it writes the resultant plots and tables to a report. The report (Fig. 8-2), a JPEG image of the CCD (Fig. 8-3), and two downloadable FITs images are linked to an online SQL database (Fig. 8-1).



DARK ENERGY
Survey

CCD Test Data DBI

s3-95-23Jun2009

Image
Stage1 Report
Dark.fits
Flat.fits
Stage2 Report

Added at 2009-07-14 10:54:43 by Montes
Current working status is 2
Lot: (2C)
Wafer: (18)
Device: (123194-18-1)
Comments: ()
Obsolete: ()

	Technical Requirements	Specification	Data
T-1.1	Nonlinearity (Left)(fraction)	< 1 %	0.1
T-1.2	Nonlinearity (Right)(fraction)	< 1 %	0.1
T-2.1	Full Well (Left)(e-)	> 130000 e-	159380
T-2.2	Full Well (Right)(e-)	> 130000 e-	167763

Fig. 8-1 View of part of a page from online database

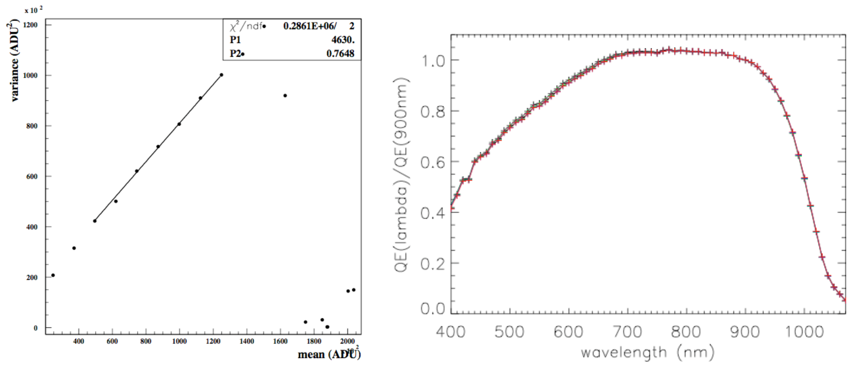


Table 2. Cosmetics Report - Dark pixels, hot pixels, and nonlinearity

Test	bad area (pixels)	total area (pixels)	percent below background
Black spots left	74	4145280	0.000892581
Black Spots right	13	4145280	0.000156805
Black Spots total	87	8290560	0.00104939
Linearity left	374	4145280	0.00451115
Linearity right	394	4145280	0.00475239
Linearity total	768	8290560	0.00926355
Hot pixels left	72	4145280	0.000868458
Hot pixels right	22	4145280	0.000265362
Hot Pixels total	94	8290560	0.00113382
Sum of all tests left	490	4145280	0.00591034
Sum of all tests right	424	4145280	0.00511425
Sum of all tests	914	8290560	0.0110246

Fig. 8-2 A few samples of the many plots and tables contained in a CCD report

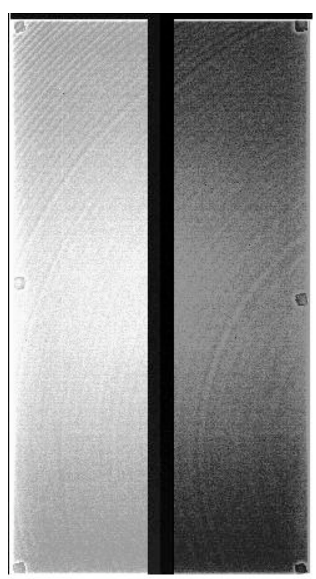


Fig. 8-3 JPEG of one CCD

9. GRADING THE CCDS

Grading the CCD is *not* automated. We look through the results in the reports and compare them to the CCD requirements. Then we investigate the images related to the tests that the CCD may have failed or to look into any "suspicious" features. A table summarizing the distribution of grades for the CCDs tested so far is shown in Fig. 9-1.

To be a science grade, a CCD, a device must pass all requirements. Science grade CCDs are safely put aside and are being saved for installation in the final focal plane. To be engineering grade, a CCD may fail one of more of the tests but can still be read out and provide very useful information about imager performance. Engineering grade devices have been used to study the operation of the prototype imager and are being used to commission the final imager. A CCD with a grade of 0.5 ("intermittent") shows defects that are a function of clock or substrate voltage or may come and go upon temperature cycling. A CCD with a grade of 0 ("failed") has missing clocks or defects so extensive that the CCD cannot even be used for commissioning studies.

Grade	*Grade*	*Frequency*
Science	2	88
Engineering	1	49
Intermittant	0.5	16
Failed	0	56
Pending further analysis	-1	0
Total		209

Fig. 9-1 Distribution of grades for 2k x 4k CCDs tested to date

10. DISCUSSION AND SUMMARY

Developing a system to efficiently test CCDs has provided DECam with enough science grade CCDs to populate the entire focal plane more than 18 months before scheduled first light for the instrument and approximately a year before they are needed to start building the final focal plane. Additionally, having timely information about which CCDs are engineering grade has provided DECam with many detectors for use in imager development and commissioning.

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